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The peculiar action of the sulphide of silver as a conductor of electricity was described by Faraday[1] in 1833. Later Hittorf,[2] in 1851, repeated Faraday's experiments and confirmed the results of the earlier work. In 1902 Streintz,[3] in a study of the conductivity of compressed powders, investigated the behavior of compressed silver sulphide in an electrical circuit and found all of the phenomena described by Faraday and Hittorf. All of these observers attribute to silver sulphide a negative coefficient of resistance for heat, Faraday speaking of it as "an extraordinary case . . . which is in direct contrast with the influence of heat upon metallic bodies."

I have recently conducted a long series of experiments upon the electrical resistance of compressed silver sulphide and, as a result of my observations, am led to the belief that many, if not all, of the phenomena described by earlier experimenters may be explained as due primarily to the condition of the contacts between the specimen of silver sulphide and the electrodes used to connect it into the electrical circuit.

In order to study the behavior of this material I have found it convenient to consider the specimen and its electrodes during three distinct stages or phases of their condition. These will be briefly described.

1st Condition. When the specimen is first placed in circuit it has an extremely high resistance. Upon heating the specimen its conductivity increases with extreme rapidity and, when the source of heat is removed, the conductivity frequently falls to nearly that which originally existed. As an illustration of this action the figures given by Streintz of test upon a sample may be quoted. "At a temperature of 100° the specimen showed a resistance from 3,000 to 1,000 ohms; at 150°, from 400 to 150 ohms; at 220° the resistance measured only from .1 to .2

[1] Faraday's Experimental Researches in Electricity, Vol. 1, 432 et seq.

[2] Hittorf, Pogg. Ann., Vol. 84, 1851.

[3] Streintz, Ann. der Physik., Vol. 3, 1900, and Vol. 8, 1902.

of an ohm; and from 230° upward, it appeared to have practically the same resistance." As also noted by Faraday the application of external heat is not necessary, as by the use of a source of current of sufficient voltage the requisite current can be obtained to heat the specimen sufficiently and "break down" its initial resistance.

2nd Condition. After the initial high resistance has been broken down and a current of some strength has passed, I have found no case where the specimen attained its original high resistance. Usually, after cooling, the resistance is but a fraction of that which originally existed but is practically always several times greater than that which exists when the specimen has become heated by a flow of current through it. This stage, where the specimen shows a gradual lowering of apparent resistance with increasing current or an increase in apparent resistance with a diminishing current, but never returns to the abnormally high initial resistance, is termed the second condition of the test.

3rd Condition. After the current has passed through the specimen for some time, — or usually more rapidly if the direction of the current has been reversed,— the characteristics of the sulphide of silver specimen in its second condition are no longer found, and the resistance of the specimen changes little with changes in current strength or with heat. This peculiarity of what is here termed the "third condition" was described by Faraday, who also noted that the properties of the specimen described under the second condition "could not be renewed until a fresh surface of the sulphuret had been applied to the positive pole. This was in consequence of peculiar results of decomposition."

Streintz's tests were made upon small cylinders of compressed silver sulphide approximately two centimeters in length and fifteen hundredths of a square centimeter in cross-section. Electrodes of platinum foil were placed at the two ends of the cylinder and two supplementary electrodes were embedded within the specimen. In my experiments plates of compressed sulphide were used, which were rectangular in shape and roughly three-quarters of an inch in length by five-sixteenths of an inch in width; the average thickness of the plates was about one thirty-second of an inch. Electrodes of platinum, silver and copper were used both in the form of fine wires or of foil. The terminals were pressed into the plates of silver sulphide and the tests conducted both while the specimen and its terminals were in the press and after they had been removed. Many of the specimens studied by me had been prepared by subjecting them to a pressure of 500,000 pounds to the square inch. The pressure used in forcing the terminals into the specimen was approximately 25,000 pounds.

The electrical measurements were made by the use of a Weston

milliammeter and voltmeter, included in circuit with the specimen, and a battery having an electro-motive force of 20 volts. The voltmeter was connected about the terminals of the specimen and the current was controlled by the use of resistance coils placed in the direct circuit with specimen, ammeter and battery. A telephone was also so arranged that it could be connected with the terminals of the specimen under test.

An extremely large number of measurements was made on many specimens under varying conditions. The characteristics of this material, as described above, were found throughout the tests and agree with those found and recorded by former experimenters. The use of the telephone in my experiments, however, has, I believe, thrown some new light upon the action which is taking place within the specimen of sulphide of silver during the passage of the electrical current through it.

Consideration of Condition I. I have frequently found that specimens had an initial resistance so high that with 20 volts no measurements of current could be made with the instruments at hand. When connected with a 110-volt lighting circuit there was an immediate fall in resistance and thereafter the 20-volt source sufficed for current measurements. Placing a heated soldering iron in the vicinity of the specimen would frequently be equally effective in lowering the initial resistance of a specimen.

The following table gives characteristic current and voltage readings of specimens when in the first condition.

TABLE I.

Voltage at Terminals.	Current Amperes.	Apparent Resistance.
18.	.06	300. ohms.
17.	.28	61. ohms.
18.	.34	53. ohms.
16.	.38	42. ohms.
4.5	.85	5.3 ohms.

This action appeared to be equally conspicuous with platinum, steel, silver or copper electrodes. During the time that the resistance of this specimen was high, violent "sputtering" or "burning" noises were audible in the telephone, and these noises entirely ceased at the time of making the last measurement recorded above. The noises heard in the telephone were characteristic of those frequently present when a current is passing through an imperfect contact. The subsidence of these noises was indicative of the formation of more perfect contacts.

The existence of these burning noises shows the presence of an imperfect connection between the specimen and one or both of its electrodes and that arcing is taking place at one or both of these places. An examination of all specimens tested has shown that violent action of some kind has taken place at the point of connection between the sulphide pellet and the electrode connected with the positive pole of the battery ; the surface of the specimen has been blackened and some of the fine wires of the electrode have been burned away. On the other hand, the negative ends of the specimens and the electrodes by means of which they have been connected with the negative pole of the battery have been invariably bright and clean.

The probable explanation of the physical action which takes place during the first condition is that despite the close mechanical association of the electrodes and the specimen there is no electrical connection, and an arc must take place between one or both electrodes and the specimen before a current can pass. To produce such an arc requires ionization either by heat or by a sufficient difference of potential at the point or points of discontinuity. It appears from all tests that this action takes place most readily at the negative electrode of the specimen, and that gradually a more or less perfect connection is established at this point. When this action takes place the excessive apparent resistance of the specimen is broken down, and the specimen may be considered as passing from the first into the second condition. In support of this explanation of this phenomenon, the following tests may be described.

The direction of the current through a specimen, the resistance of which had been broken down, was reversed. The noises in the telephone which previously had been present were no longer apparent, and after a short time the changes in resistance characteristic of the second condition ceased to exist and the specimen passed into the third condition. Again, a specimen which was in the third condition had one of its electrodes removed and, after the surface of the specimen had been carefully cleaned where the electrode had previously been, it was clamped under great pressure in the jaws of a steel vise with soft copper surfaces. The figures obtained in this test are given below.

From these figures it will be seen that a perfect connection had been established between the original terminal and the sulphide, but that a good connection had not been made at the terminal which had been clamped in the vise. During the test, while the current was passing from the vise to the sulphide, the noise in the telephone was very great, but when the current was passing through the imperfect connection in the opposite direction no noises could be detected. After the

TABLE II.

Current from Vise to Ag_2S.			Current from Ag_2S to Vise.		
Voltage at Terminals.	Current Amperes.	Apparent Resistance.	Voltage at Terminals.	Current Amperes.	Apparent Resistance.
1.10	.210	5.2	.5	.210	2.4
2. to 3.	.350	..	.48	.390	1.2
1. to 3.	.520	..	.5	.540	.9
2.	.650	3.			
2.5 to	.850 to	..			
3.5	.900	..			

current had passed for a short time a good connection was established at the terminal in the vise and the third condition of the action was established.

What actually takes place at the negative electrode I have not determined. Both Faraday and Hittorf were inclined to the belief that conduction through the sulphide of silver is electrolytic, and Hittorf states that silver was found by him at the junction with the negative electrode. Hittorf also found that, in similar tests made with the oxide of copper, antennae of copper were thrown out from the specimen at the negative pole.

Consideration of Condition II. The second condition exists when a more or less perfect connection has been established at the negative electrode and the contact at the positive terminal is still faulty. All tests of specimens in this condition show the characteristics of measurements of currents and potentials at imperfect contacts in an electrical circuit. The really remarkable peculiarity of the silver sulphide is that contact cannot be established even when the electrodes and the specimen are pressed together under a weight of many tons.

Attention might be called to the fact that there is present a condition of "unilateral" conduction such as has been extensively studied by Professor Pierce,[4] the magnitude of the action being dependent upon the degree to which perfect contact has been obtained at the negative terminal of the specimen. This differential action is shown in Table II., and Table III. given below as a fairly characteristic set of measurements made upon specimens in the second condition. It should be noted that the repeated reversals of current gradually establish perfect connections at the two terminals of the specimen, and thus rapidly obliterate the unilateral conduction and tend to establish the third condition.

[4] Pierce, Physical Review, **25** (1907); **28** (1909).

TABLE III.

			Current Reversed.		
Voltage at Terminals.	Current Amperes.	Apparent Resistance.	Voltage at Terminals.	Current Amperes.	Apparent Resistance.
.42	.072	5.8	.27	.072	3.7
.54	.110	4.9	.36	.110	3.2
.82	.200	4.1	.54	.202	2.6
1.08	.310	3.5	.72	.310	2.3
1.04	.350	3.0	.70	.350	2.0
1.04	.405	2.5	.80	.410	1.9
1.16	.480	2.4	.90	.500	1.8
1.38	.640	2.1	1.04	.640	1.6
1.60	.850	1.8	1.30	.830	1.5
1.90	1.350	1.4	1.60	1.300	1.2

It is this second condition which has been specially studied by previous experimenters, and it has been due to the measurements made while the contacts between the electrodes and the specimen were in the condition above described that the negative coefficient of resistance for heat has been attributed to silver sulphide. Increasing temperature of the specimen or increasing difference of potential at its terminals simply promotes the ionization at the imperfect contact or contacts and permits a greater flow of current.

Consideration of Condition III. The condition which I have called the third is that in which fairly good connections have been established between both electrodes and the specimen, and is characterized by an absence of noise in the telephone, with the current passing through the specimen in either direction. The figures given in Table IV. are those obtained from continued tests of the sample, the apparent resistances of which are given in Table III. after it had passed into the third condition.

TABLE IV.

Voltage at Terminals.	Current Amperes.	Apparent Resistance.	Voltage at Terminals.	Current Amperes.	Apparent Resistance.
.08	.072	1.11	.08	.072	1.11
.122	.110	1.11	.122	.110	1.11
.36	.31	1.16	.35	.305	1.15
.58	.500	1.16	.58	.500	1.16
.74	.63	1.17	.74	.63	1.17
1.00	.85	1.17	1.00	.85	1.17

The characteristics of the second condition, it will be seen, have entirely disappeared, and the resistance with increasing current or temperature instead of falling appears to have increased. As stated by Faraday, the removal of the positive electrode from the specimen, and the scraping of the surface so as to present a new layer of the sulphide restores in every case the specimen to the properties previously possessed by it under the second condition.

The conclusions which may be drawn from the above are :

(a) That electrical connection cannot be made between compressed silver sulphide and electrodes of platinum, steel, silver or copper simply by pressure.

(b) That conduction through compressed silver sulphide cannot be obtained until sufficient ionization has occurred at the contacts to allow the passage of an arc.

(c) That connection, when a current has passed, is most readily and completely obtained at the negative terminal of the specimen.

(d) That it is probable that, when perfect connections have been established between the sulphide of silver and its electrodes, the sulphide has a positive rather than a negative coefficient of resistance for increasing temperatures.

Boston, January 25, 1910.